Why Are Sliding Seats and Short Stroke Intervals Used for Racing Shells?

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Goals

- Explain and answer the title questions: Why sliding seats? Why short stroke intervals?
- Show how a drastically simplified model can give useful insights and quantitative results.

The Rowing Cycle (1)

- Stroke—oars in water, moving sternward
- Run—oars out of water, moving ‘bow’ward
- Catch—beginning of stroke
- Recovery—end of stroke

The Rowing Cycle (2)

Item	Background Crew	Foreground Crew
When	Just after catch	Just before recovery
Knees	Bent	Straight
Arms	Stretched	Bent
Leaning	Sternward	Bowward
Seats	Near sternward stops	Near bowward stops
Oars	$\approx$ 60 deg bowward	$\approx$ 30 deg sternward

Dan Pope

- ‘Crewed’ as an Undergraduate
- Foundation paper: “On Men and Boats and Oars” (1973),
  - Describes and parameterizes
  - Develops a predictive dynamic model

Basic Conclusion:

THE racing shell system was (and apparently still is) NEARLY OPTIMUM, because
its ‘generalized design’ had evolved under intense competition,
over many racing seasons,
in an almost constant environment.

Belaboring the Optimality:

Last major design improvement: sliding seats in 1869.

Seemingly small effect: recent materials revolution [rule changes?]

The system is optimal—the model has to explain why. (Pope's model characterizes the system using about 8 parameters. Judge merit of model by the closeness to optimality of a realistic set of parameter choices.)

Pope's Racing Shell Data: (1)

- 2,000 m, 6 min (18.23 ft/sec) races are often won by a few feet.
- shells are about 60 ft long, 22-25 in wide, 14 in deep, and they draw 8-10 in.
- shell centerline to oarlock is about 32 in; oarlock to center of blade is about 90 in.
- seats slide fore-aft 27 in.
- eight 200 lb oarsmen, one 100 lb coxswain, and a shell weight of 250-280 lb.

Pope's Racing Shell Data: (2)

- two general oar-blade styles; area of each is about 180 in^2.
- oar angle from about 60 deg bowward of a normal to hull at catch, to about 30 deg sternward at recovery.
- fore/aft amplitudes of centers of oar blades are about 10.25 ft.

Pope's Racing Shell Data: (3)

- 1968 Olympic mean rower weight progression: (scullers = 183 lb) $<$ (all oarsmen = 191 lb) $<$ (all men from eights = 198 lb) [Master's thesis?]
- Rate of stroking, or rating: 30 - 40 cycles/min; so period, T, varies between 2.0 - 1.5 sec
- Stroke fraction, $\alpha \equiv \frac{\text{stroke time}}{\text{stroke + run times}}$; 0.35 < α < 0.40
- "Measurements of dynamical quantities of interest are scattered, fragmentary, and undependable; data taken under competitive conditions is virtually non-existent."

Questions:

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Smoother is generally better unless it's not.

Stroke fraction, $\alpha > 0.4$, would be smoother. Why is α so low in an optimum design?

Fixed seats would be smoother (cause lower hull velocity excursions). Why use sliding seats in an optimum design?

Model Requirements:

- Be tractable (need to simplify drastically)
- Give meaningful results (need to keep 'essential' features)

Five Model 'Components':

1. Hull drag
2. Oar thrust
3. Kinematics (combining velocities)
4. Cyclic impulse/momentum balances
5. Cyclic work/energy balances

Modeling Hull Drag:

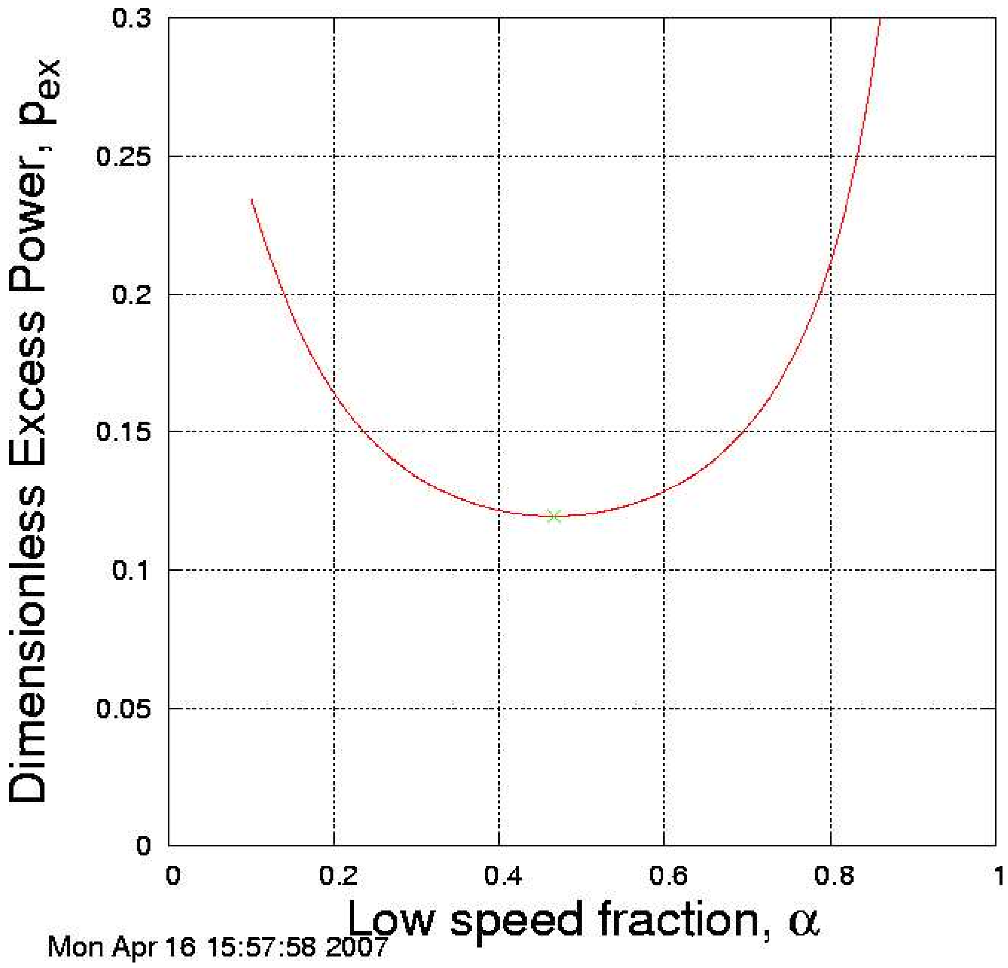
- Simplifying assumptions include:
  rigid hull, one coordinate, steady-state
- High Reynolds number flow (Re $\approx 1.7 \cdot 10^8$)
  Wellicome's 1967 tests: wave drag is about 0.07 of total
- $F_{dr} = \frac{1}{2}$ 1.07 $C_{dr}\ \rho v^2\ A_{wet}$, 1.07 is wave drag factor,
  $C_{dr} \approx$ 0.0024, $A_{wet} \approx$ 102 ft^2,
  $\rho \approx$ 62.5/32.2 lbf sec^2/ft^4
- $F_{dr} = k_{dr} v^2$, with $k_{dr} =$ 0.254 lbf sec^2/ft^2

Drag Only Results (1):

- Constant speed drag is about 84 lb at $\bar{v} =$ 18.23 ft/sec (2000 m in 6 min)
- Requires about 0.35 hp/man
- Real diversion: Lance Armstrong at 154 lb developed about 0.64 hp (480 watt) for 30 min
- Essential part of talk: Slow constant speed at first; then switch to higher constant speed: $v_{lo} = \bar{v} - \Delta v/(2\alpha)$ until αT; then $v_{hi} = \bar{v} + \Delta v/(2(1-\alpha))$ until T; average velocity is still $\bar{v}$; average absolute velocity departure from $\bar{v}$ is Δv

Drag Only Results (2):

Two speed drag power, $P_{dr} = k_{dr}\bar{v}^3\{1 + p_{ex}\}$, where the dimensionless excess power, $p_{ex} = \frac{3}{4}(\frac{\Delta v}{\bar{v}})^2(\frac{1}{\alpha(1-\alpha)}) + \frac{1}{8}(\frac{\Delta v}{\bar{v}})^3(\frac{1}{(1-\alpha)^2} - \frac{1}{\alpha^2})$. The plot shows $p_{ex}(\alpha)$ for $\frac{\Delta v}{\bar{v}} = 0.2$.



Drag Only Results (3):

For $\frac{\Delta v}{\bar{v}} = 0.2$, minimum two-speed-strategy drag penalty $p_{ex\,min} \approx 0.12$ at $\alpha_{min} \approx 0.47$.

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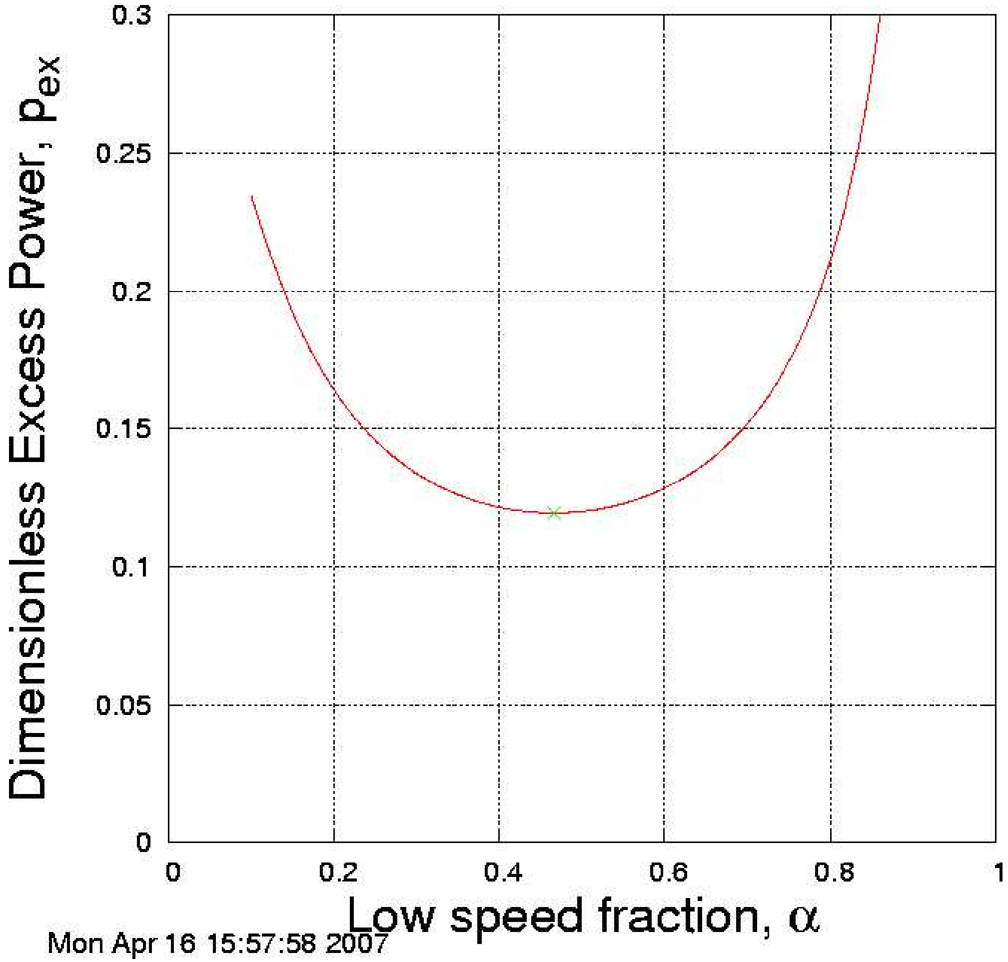
One two-speed-cycle in 6 min formally same as 200 two-speed cycles (1.8 s/cycle). (Points to) answer to 'short stroke interval' question.



Modeling Oar Thrust (1):

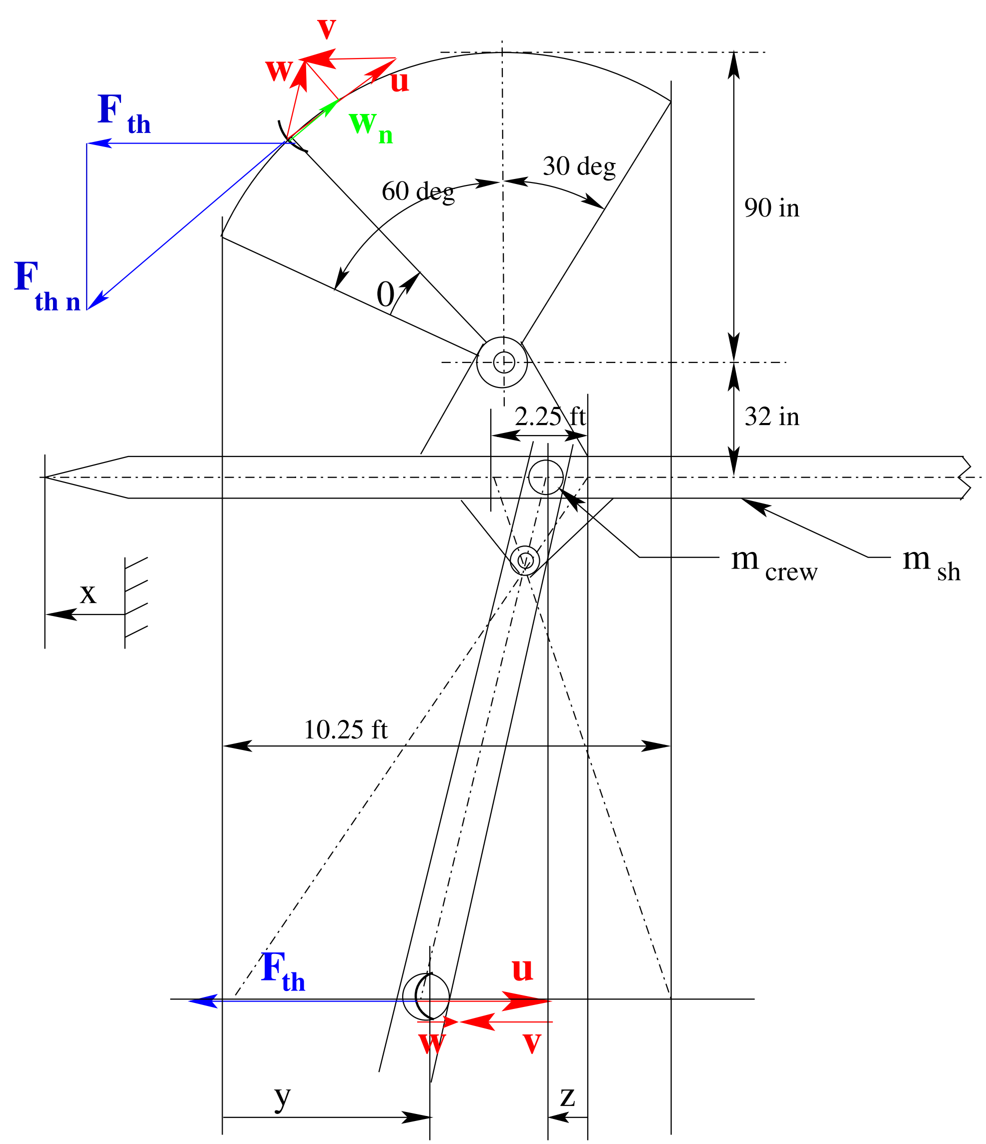
- Pope, like Wellicome, drastically simplifies; assumes surface-piercing-flat-plate, steady-state:
- $F_{th\,n} = \frac{1}{2} C_{th} \rho w_n^2 A_{th}, \quad F_{th\,n}$ is total normal force exerted by the water, $C_{th} \approx 1.0$, $A_{th} \approx 10\,\text{ft}^2$, and w_n is normal component of blade velocity with respect to (WRT) still water,
- $F_{th\,n} = k_{th} w_n^2$ with $k_{th} = 11.64$
- Note: $C_{dr} \ll C_{th}$ and A_{th} as large as practicable

Modeling Oar Thrust (2):

- Pope's drastically simplified oar thrust model still includes a basic feature of the real system:
- Oars develop thrust at a relatively low energy cost
- Pope includes oar angularity in his model;
  I simplify further and do not
- $F_{th} = \frac{1}{2}C_{th}\rho w^2 A_{th}$, where F_{th} is the bowward force exerted on the oar blades by the water and w is the sternward component of the velocity of the centers of the oar blades WRT still water.

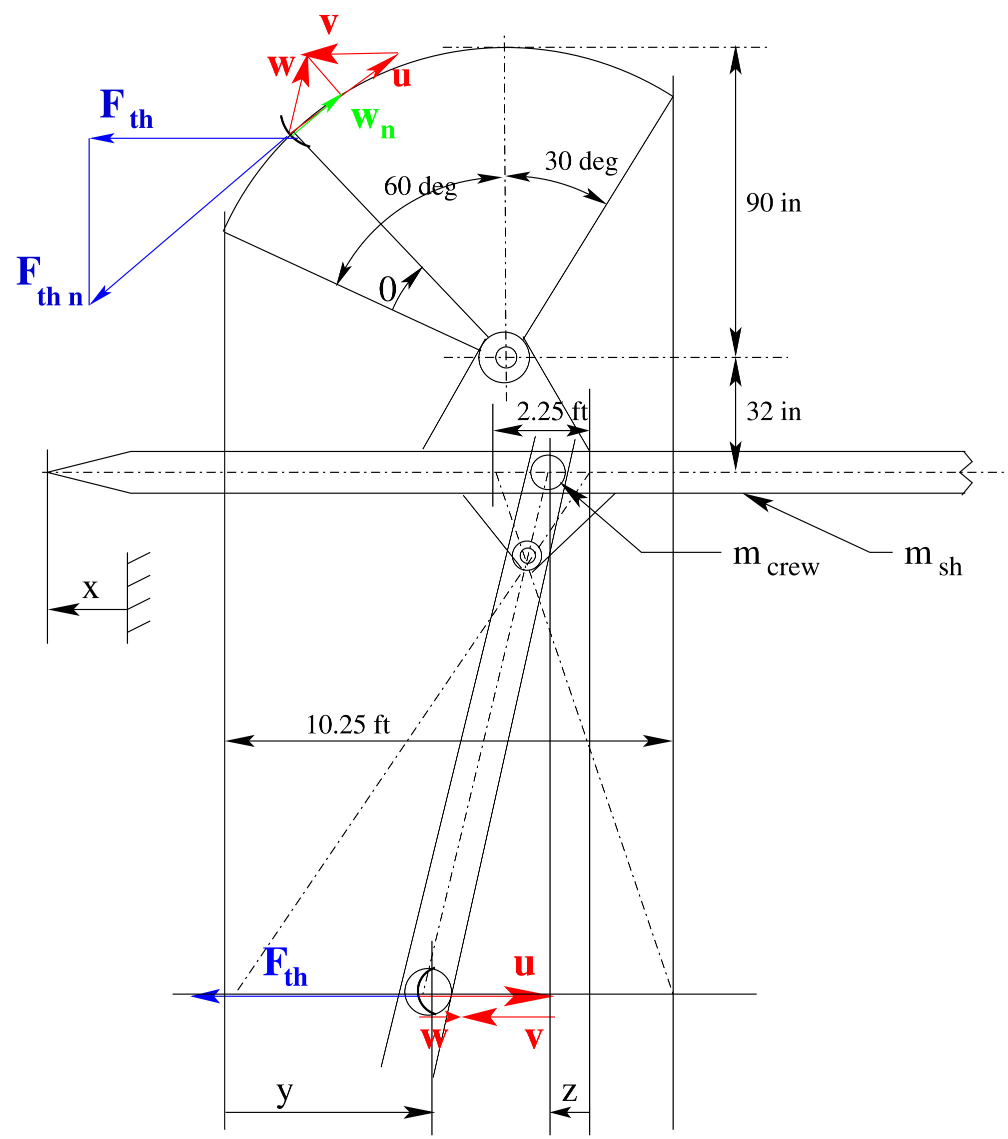
Modeling Kinematics (1):

- Top: Pope's oar model
- Bottom: Zero rotation model
- $w = u - v$
- Zero should be θ



Modeling Kinematics (2):

- Assume proportionality:
- $\frac{z}{2.25} = \frac{\theta}{90\text{ deg}}$
- $\frac{z}{2.25} = \frac{y}{10.25}$
- Assume uniform relative velocity:
- $\dot{\theta} = \frac{90\text{ deg}}{\alpha T}$
- $\dot{y}(\equiv u) = \frac{10.25}{\alpha T}$
- $\dot{z}_{st} = \frac{2.25}{\alpha T}$
- $\dot{z}_{run} = \frac{-2.25}{(1-\alpha)T}$



Power Cost Of Developing Thrust:

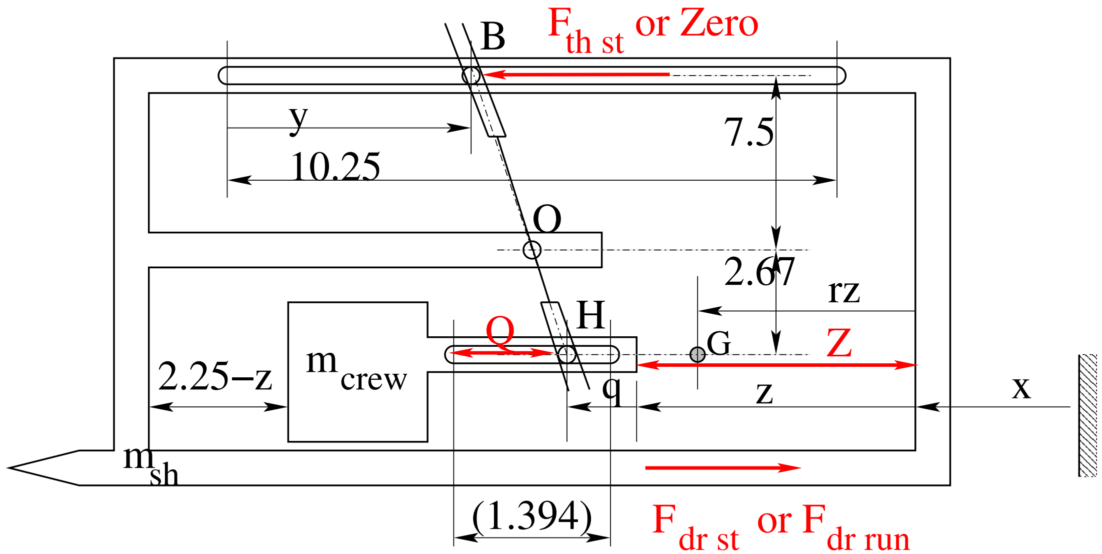
- All pieces of model are in place
- Model is straightforward, but cumbersome
- Take to limit to intuitively show power cost of developing thrust
- Constant speed, continuous thrust, no sliding seat limit
- Cyclic Impulse/Momentum Balance

  $$F_{th}T = F_{dr}T \Rightarrow \bar{w} = \bar{v}\sqrt{k_{dr}/k_{th}}$$

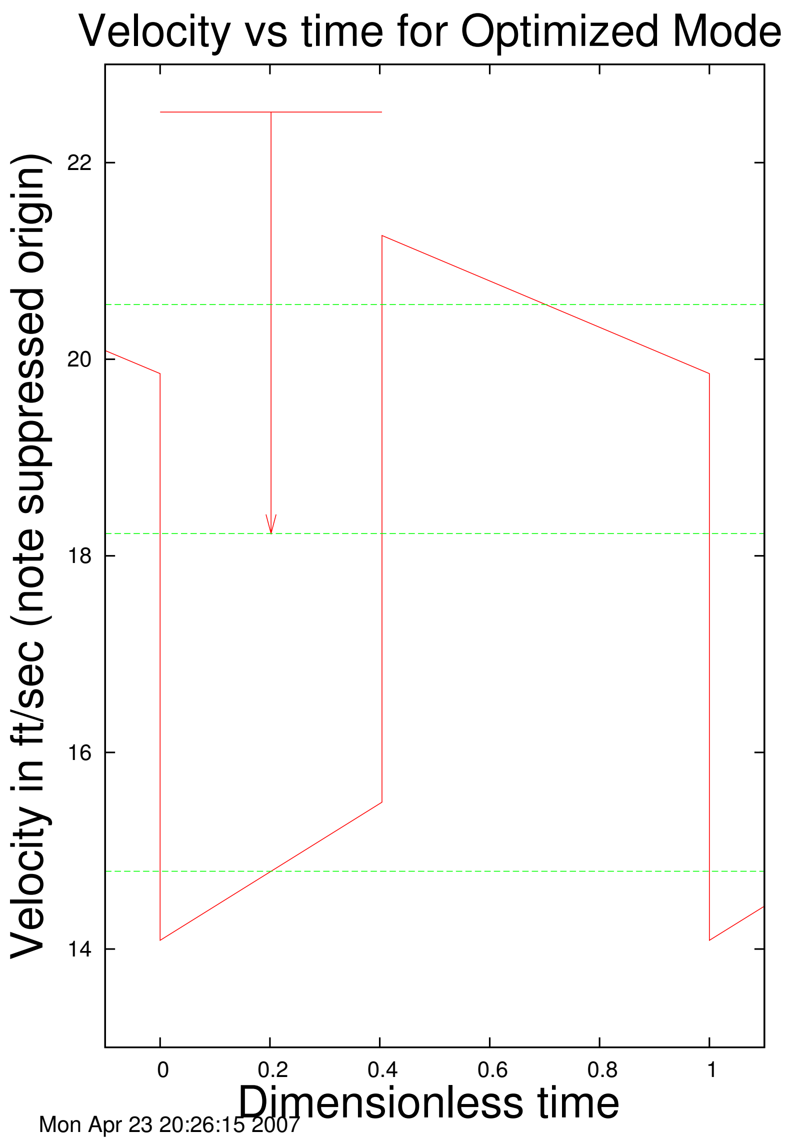
- Cyclic Work/Energy Balance

  $$F_{dr}\bar{v}T + F_{th}\bar{w}T = P_{acct}T \Rightarrow P_{acct} = k_{dr}\bar{v}^3[1 + \sqrt{k_{dr}/k_{th}}]$$

Model and Real System



Optimized Model:



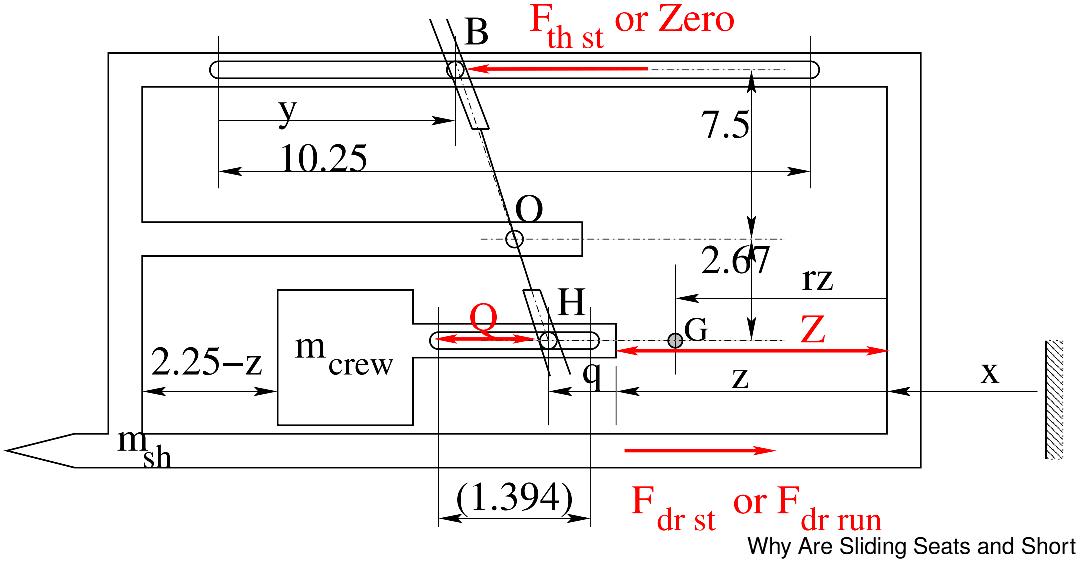
$$\frac{10.25+2.25r}{\alpha T} = 22.51,$$
$$v_{rec+} = 21.26,$$
$$\bar{v}_{run} = 20.56,$$
$$v_{cat-} = 19.85,$$
$$\bar{v} = 18.23,$$
$$v_{rec-} = 15.49,$$
$$\bar{v}_{st} = 14.79,$$
$$v_{cat+} = 14.09,$$
$$\Delta v_{rec} = -\Delta v_{cat} = 5.77,$$
$$\Delta v_{st} = -\Delta v_{run} = 1.40.$$

Model Equations:

- Variables: $\bar{v}, \alpha, T$
- Parameters: $r \equiv m_{crew}/(m_{crew} + m_{sh})$, k_{dr}, k_{th}, 10.25 ft, $2.25r$ ft, P_{max}, $90/32$ (implicit)
- Cyclic Impulse/Momentum Balance:
  $\alpha T k_{th}[\frac{10.25+2.25r}{\alpha T} - \bar{v}]^2 - \alpha T k_{dr}[\bar{v} - \frac{2.25r}{\alpha T}]^2 -$
  $(1-\alpha)T k_{dr}[\bar{v} + \frac{2.25r}{(1-\alpha)T}]^2 = 0$
- Cyclic Work/Energy Balance:
  $P_{max}T = \alpha T k_{th}[\frac{10.25+2.25r}{\alpha T} - \bar{v}]^3 + \alpha T k_{dr}[\bar{v} - \frac{2.25r}{\alpha T}]^3 +$
  $(1-\alpha)T k_{dr}[\bar{v} + \frac{2.25r}{(1-\alpha)T}]^3$

Answers

- Why sliding seats? To allow the blade centers to move fast enough WRT the shell during the stroke so that they push water sternward, thereby propelling the shell.
- Why short stroke intervals? To reduce the sum of the power necessary to develop thrust and the excess drag power caused by hull velocity fluctions about average hull velocity.



With sliding seats.

$$\bar{w}_{st} = \bar{u}_{st} - \bar{v}_{st} = \left[\frac{(1.39+2.25)\frac{90}{32}}{\alpha T}\right] - \left[18.23 - \frac{2.25r}{\alpha T}\right]$$

$$\bar{w}_{st} = \frac{10.25+2.25r}{\alpha T} - 18.23$$

Without sliding seats.

$$\bar{w}_{st} = \bar{u}_{st} - \bar{v}_{st} = \left[\frac{(1.39)\frac{90}{32}}{\alpha T}\right] - [18.23]$$

$$\bar{w}_{st} = \frac{3.92}{\alpha T} - 18.23$$